

**CORRECTED
VERSION***

PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau



INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 :

**D01F 9/12, B32B 9/00
C01B 31/04**

A1

(11) International Publication Number:

WO 91/05089

(43) International Publication Date:

18 April 1991 (18.04.91)

(21) International Application Number: PCT/US90/05498

(22) International Filing Date: 27 September 1990 (27.09.90)

(30) Priority data:

413,837 28 September 1989 (28.09.89) US
413,838 28 September 1989 (28.09.89) US
413,844 28 September 1989 (28.09.89) US

(71) Applicant: HYPERION CATALYSIS INTERNATIONAL, INC. [US/US]; 128 Spring Street, Lexington, MA 02173 (US).

(72) Inventors: FRIEND, Stephen, O. ; 375 Main Street, Oxford, MA 01921 (US). ATKINS, Jaspard, Harvey ; 1536 High Street, Westwood, MA 02090 (US). TENNENT, Howard, G. ; 301 Chandler Mill Road, Kennett Square, PA 19348 (US). HAUSSLEIN, Robert ; 20 Slocum Road, Lexington, MA 02173 (US). MOY, David ; 21 Edward Drive, Winchester, MA 01890 (US). CHISHTI, Asif ; 1251 Pawtucket Boulevard, Unit #1, Lowell, MA 01854 (US).

(74) Agent: FRENCH, Timothy, A.; Fish & Richardson, One Financial Center, Suite 2500, Boston, MA 02111-2658 (US).

(81) Designated States: AT, AT (European patent), AU, BB, BE (European patent), BF (OAPI patent), BG, BJ (OAPI patent), BR, CA, CF (OAPI patent), CG (OAPI patent), CH, CH (European patent), CM (OAPI patent), DE*, DE (European patent)*, DK, DK (European patent), ES, ES (European patent), FI, FR (European patent), GA (OAPI patent), GB, GB (European patent), HU, IT (European patent), JP, KP, KR, LK, LU, LU (European patent), MC, MG, ML (OAPI patent), MR (OAPI patent), MW, NL, NL (European patent), NO, RO, SD, SE, SE (European patent), SN (OAPI patent), SU, TD (OAPI patent), TG (OAPI patent).

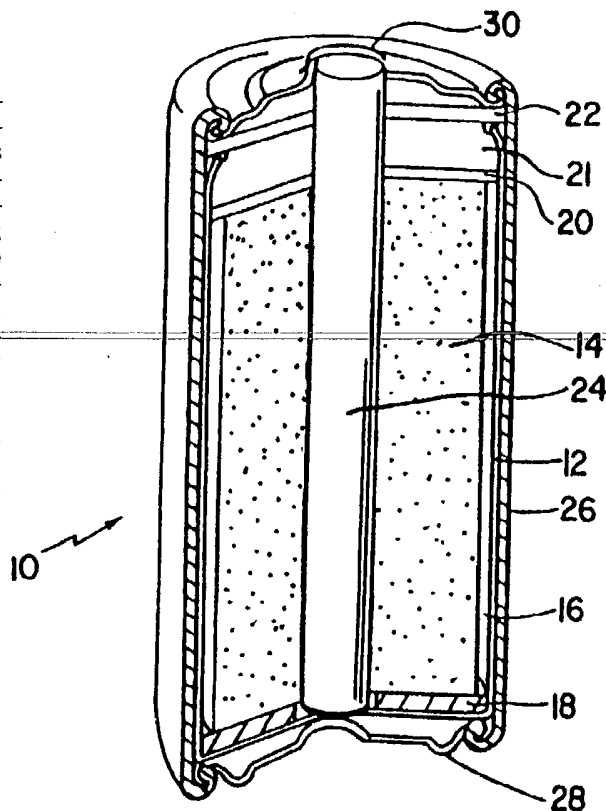
Published

With international search report.

(54) Title: BATTERY

(57) Abstract

In one aspect, a fibril aggregate that includes a multiplicity of carbon fibrils whose longitudinal axis have substantially the same relative orientation, each of the fibrils characterized as having graphitic layers that are substantially parallel to its longitudinal axis and being free of a continuous thermal carbon overcoat and a method for preparing such aggregates. In another aspect, an improved battery (10) having an anode (12), a cathode (14) that includes a chemically reducible material into which is incorporated an amount of electrically conductive carbon microfibers sufficient to enhance the electrical conductivity of the chemically reducible material and an electrolyte. In another aspect, an improved electrochemical cell having a catalytic electrode on which an electrochemical reaction occurs which has incorporated therein carbon microfibers having diameters less than 0.1 micron in an amount sufficient to enhance the electrical conductivity of the electrode.



DESIGNATIONS OF "DE"

Until further notice, any designation of "DE" in any international application whose international filing date is prior to October 3, 1990, shall have effect in the territory of the Federal Republic of Germany with the exception of the territory of the former German Democratic Republic.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria	ES	Spain	MC	Monaco
AU	Australia	FI	Finland	MG	Madagascar
BB	Barbados	FR	France	ML	Mali
BE	Belgium	GA	Gabon	MR	Mauritania
BF	Burkina Faso	GB	United Kingdom	MW	Malawi
BG	Bulgaria	GR	Greece	NL	Netherlands
BJ	Benin	HU	Hungary	NO	Norway
BR	Brazil	IT	Italy	PL	Poland
CA	Canada	JP	Japan	RO	Romania
CF	Central African Republic	KP	Democratic People's Republic of Korea	SD	Sudan
CG	Congo	KR	Republic of Korea	SE	Sweden
CH	Switzerland	LI	Liechtenstein	SN	Senegal
CM	Cameroon	LK	Sri Lanka	SU	Soviet Union
DE	Germany	LU	Luxembourg	TD	Chad
DK	Denmark			TG	Togo
				US	United States of America

- 1 -

BATTERY

Background of the Invention

This invention relates to electrochemical cells and to preparing carbon fibrils.

Batteries are a type of electrochemical cell containing an anode, a cathode, and an electrolyte in which the anode and cathode are permanently contained within the cell. Batteries containing a metal anode, metal oxide cathode, and an electrolyte are known. Because metal oxides generally are poor electrical conductors (their conductivities are in the semiconducting to insulating range), an electrically conductive material is added to the metal oxide to render the cathode electrically conductive.

Fuel cells are a type of electrochemical cell in which the cathodic and anodic reactants are fed to the cell from an external source during operation, rather than being permanently contained within the cell. The reactants contact electrodes which catalyze the reduction of the cathodic reactant and the oxidation of the anodic reactant; the electrodes themselves are not consumed in the reaction. The electrodes also collect the current generated as a result of the electrochemical oxidation and reduction reactions.

Metal-air cells are similar to fuel cells except that only the cathodic reactant is fed to the cell. The anodic reactant is a metal which forms a permanent part of the cell.

Carbon microfibers (i.e. fibers having diameters less than 1 micron) are also known. Microfibers having diameters less than 0.5 micron are referred to as fibrils. They may be prepared by contacting a metal-containing

- 2 -

catalyst with a carbon-containing gas at elevated temperatures.

Summary of the Invention

5 In one aspect, the invention features an improved battery having an anode, a cathode that includes a chemically reducible material into which is incorporated an amount of electrically conductive carbon microfibers sufficient to enhance the electrical conductivity of the chemically reducible material, and an electrolyte.

10 In preferred embodiments, the microfibers have diameters no greater than 0.1 micron and length to diameter ratios of at least 5. Even more preferred are carbon microfibers that are tubes having graphitic layers that are substantially parallel to the microfiber axis and diameters
15 between 3.5 and 75 nanometers, inclusive, as described in Tennent, U.S. Pat. No. 4,663,230 ("Carbon Fibrils, Method for Producing Same and Compositions Containing Same"), Tennent et al., U.S.S.N. 871,676 filed June 6, 1986 ("Novel Carbon Fibrils, Method for Producing Same and Compositions
20 Containing Same"), Tennent et al., U.S.S.N. 871,675 filed June 6, 1986 ("Novel Carbon Fibrils, Method for Producing Same and Encapsulated Catalyst"), Snyder et al., U.S.S.N. 149,573 filed January 28, 1988 ("Carbon Fibrils"), Mandeville et al., U.S.S.N. 285,817 filed December 16, 1988
25 ("Fibrils"), and McCarthy et al., U.S.S.N. 351,967 filed May 15, 1989 ("Surface Treatment of Carbon Microfibers"), all of which are assigned to the same assignee as the present application and are hereby incorporated by reference. One aspect of substantial parallelism is that the projection of
30 the graphite layers on the microfiber axis extends for a relatively long distance in terms of the external diameter

- 3 -

of the microfiber (e.g., at least two microfiber diameters, preferably at least five diameters), as described in Snyder et al., U.S.S.N. 149,573. These microfibers preferably are also substantially free of a continuous thermal carbon overcoat (i.e. pyrolytically deposited carbon resulting from thermal cracking of the gas feed used to prepare the microfibers). These microfibers also are preferably in the form of aggregates in which individual microfibers are randomly entangled with each other or oriented substantially parallel to each other.

Preferred batteries include both primary (i.e. non-rechargeable) batteries and secondary (i.e. rechargeable) batteries. Examples of preferred batteries include reserve batteries, alkaline batteries (e.g., alkaline zinc - manganese dioxide batteries), and Leclanche batteries. The chemically reducible material for the cathode preferably includes a metal oxide (e.g., MnO_2 , HgO , Ag_2O , AgO , PbO_2 , or NiOOH), a metal chloride (e.g., CuCl), a metal sulfide (e.g., FeS), or sulfur. The anode preferably includes Zn, Li, Cd, Ag, Mg, Fe, Na, Li-Al alloy, or Pb metal.

In the case of a Leclanche or alkaline zinc - manganese dioxide battery, the amount of microfibers incorporated into the cathode preferably is less than 0.5 grams per gram of chemically reducible material, more preferably less than 0.2 grams.

The invention also features a method for preparing the battery. Preferably, the microfibers are milled or co-milled with the chemically reducible material. Preferred milling methods include mechanical and chemical milling (by exposure to a chemical reagent that decreases the microfiber

- 4 -

length, e.g., by chopping the microfiber). A preferred method for preparing the battery involves growing the chemically reducible material in situ within the electrically conductive network formed by the carbon microfibers.

The invention provides a battery having high energy density. The battery exhibits a long discharge lifetime and high utilization of the chemically reducible material. The microfibers enable the cathode to retain an effective amount of electrolyte for efficient operation. This ability is maintained even after vigorously mixing the microfibers and chemically reducible material to form the cathode. Moreover, high amounts of the chemically reducible material can be incorporated in the cathode.

In a second aspect, the invention features an improved electrochemical cell that includes a catalytic electrode on which an electrochemical reaction occurs into which is incorporated an amount of electrically conductive carbon microfibers having diameters less than or equal to 0.1 micron sufficient to enhance the electrical conductivity of the electrode.

In preferred embodiments, the electrochemical cell is a fuel cell (e.g., a hydrogen/oxygen fuel cell) or a metal-air cell (e.g., in which the metal is zinc).

Preferred microfibers have length to diameter ratios of at least 5. Even more preferred are carbon microfibers that are tubes having graphitic layers that are substantially parallel to the microfiber axis and diameters between 3.5 and 75 nanometers, inclusive, as described in Tennent, U.S. Pat. No. 4,663,230 ("Carbon Fibrils, Method for Producing Same and Compositions Containing Same"),

- 5 -

Tennent et al., U.S.S.N. 871,676 filed June 6, 1986 ("Novel Carbon Fibrils, Method for Producing Same and Compositions Containing Same"), Tennent et al., U.S.S.N. 871,675 filed June 6, 1986 ("Novel Carbon Fibrils, Method for Producing Same and Encapsulated Catalyst"), Snyder et al., U.S.S.N. 149,573 filed January 28, 1988 ("Carbon Fibrils"), Mandeville et al., U.S.S.N. 285,817 filed December 16, 1988 ("Fibrils"), and McCarthy et al., U.S.S.N. 351,967 filed May 15, 1989 ("Surface Treatment of Carbon Microfibers"), all of which are assigned to the same assignee as the present application and are hereby incorporated by reference. One aspect of substantial parallelism is that the projection of the graphite layers on the microfiber axis extends for a relatively long distance in terms of the external diameter of the microfiber (e.g., at least two microfiber diameters, preferably at least five diameters), as described in Snyder et al., U.S.S.N. 149,573. These microfibers preferably are also substantially free of a continuous thermal carbon overcoat (i.e. pyrolytically deposited carbon resulting from thermal cracking of the gas feed used to prepare the microfibers). These microfibers also are preferably in the form of aggregates in which individual microfibers are randomly entangled with each other or oriented substantially parallel to each other.

25 Incorporating small diameter carbon microfibers in one or both of the catalytic electrodes enables the electrode to collect current efficiently. The microfibers also increase the surface area of the electrode.

30 In a third aspect, the invention features a fibril aggregate that includes a multiplicity of carbon fibrils whose longitudinal axes have substantially the same relative

- 6 -

orientation, each of the fibrils characterized as having graphitic layers that are substantially parallel to its longitudinal axis and being free of a continuous thermal carbon overcoat (i.e. pyrolytically deposited carbon

5 resulting from thermal cracking of the gas feed used to prepare the fibrils). One aspect of substantial parallelism is that the projection of the graphitic layers on the fibril's longitudinal axis extends for a relatively long distance in terms of the external diameter of the fibril

10 (e.g., at least two fibril diameters, preferably at least five diameters), as described in Snyder et al., U.S.S.N. 149,573 filed January 28, 1988 and entitled "Carbon Fibrils" which is assigned to the same assignee as the present application and hereby incorporated by reference.

15 Carbon fibrils having substantially parallel graphitic layers are also described in Tennent, U.S. Pat. No. 4,663,230 ("Carbon Fibrils, Method for Producing Same and Compositions Containing Same"), Tennent et al., U.S.S.N. 871,676 filed June 6, 1986 ("Novel Carbon Fibrils, Method

20 for Producing Same and Compositions Containing Same"), Tennent et al., U.S.S.N. 871,675 filed June 6, 1986 ("Novel Carbon Fibrils, Method for Producing Same and Encapsulated Catalyst"), Mandeville et al., U.S.S.N. 285,817 filed December 16, 1988 ("Fibrils"), and McCarthy et al., U.S.S.N.

25 351,967 filed May 15, 1989 ("Surface Treatment of Carbon Microfibers"), all of which are assigned to the same assignee as the present application and are hereby

incorporated by reference.

In preferred embodiments, the diameters of at least

30 90% (and, more preferably, substantially all) of the fibrils in the aggregate have diameters between 3.5 and 75

- 7 -

nanometers, inclusive. Similarly, at least 90% (and, more preferably, substantially all) of the individual fibrils in the aggregate have a length to diameter ratio of at least 5. The diameter of the aggregate preferably is between 0.05 and 50 μm , inclusive, and the length preferably is between 0.1 and 1000 μm , inclusive.

In a fourth aspect, the invention features a process for preparing an aggregate of carbon fibrils by contacting a particulate metal catalyst deposited on a support having one or more readily cleavable planar surfaces and a surface area of at least 1 m^2/g with a carbon-containing gas in a reactor at reaction conditions including temperature sufficient to produce the aggregate.

In preferred embodiments, the support is a metal oxide, e.g., γ -alumina or magnesia, both of which are in the form of aggregates of tabular, prismatic, or platelet crystals. Preferred catalysts include iron. They may further include at least one element chosen from Group V (e.g., vanadium), VI (e.g., molybdenum, tungsten, or chromium), VII (e.g., manganese), or the lanthanides (e.g., cerium). Also preferred are catalysts that include cobalt, nickel, manganese, or a combination of copper and zinc. The catalysts may be prepared using either aqueous or non-aqueous solvents.

Preferred reaction temperatures are between 400 and 850°C, more preferably between 600 and 750°C. Preferred aggregates are those aggregates described above in which the longitudinal axes of the fibrils making up the aggregate all have substantially the same relative orientation.

The invention also features a particulate, carbon fibril-forming, metal catalyst deposited on a support having

- 8 -

one or more readily cleavable planar surfaces and a surface area of at least $1 \text{ m}^2/\text{g}$. Preferred catalyst and support materials are those described above.

The invention provides a process for preparing
5 fibril aggregates in which the texture of the aggregate is controlled by the choice of catalyst support. Using supports having one or more readily cleavable planar surfaces produces fibril aggregates having the appearance of
10 combed yarn in which the individual fibrils are straight to slightly bent or kinked. Aggregates having loose, open mat textures in which the individual fibrils are straight to slightly bent or kinked may also be produced. These aggregates are readily dispersed, making them useful in composite fabrication where uniform properties throughout
15 the structure are desired. The substantial linearity of the individual fibril strands also makes the aggregates useful in EMI shielding and electrical applications, e.g., the devices described in Friend et al., U.S.S.N. _____ entitled "Battery" and Friend et al., U.S.S.N. _____
20 entitled "Electrochemical Cell", both of which were filed on the same day as the present application, assigned to the same assignee as the present application, and hereby incorporated by reference in their entirety.

Other features and advantages of the invention will
25 be apparent from the following description of the preferred embodiments thereof, and from the claims.

Description of the Preferred Embodiments

We first briefly describe the Figure.

The Figure is a cross-sectional view, partially
30 broken away, of a battery embodying the invention.

- 9 -

Battery

Carbon microfibers are suitable in the cathodes of a wide variety of battery systems. Typically, these batteries feature an electrically conductive metal that acts as an anode and a chemically reducible material as the cathode. The particular cathode material is chosen based upon the anode material, as one of ordinary skill in the art will readily appreciate. Examples of suitable anode-cathode combinations (taken from Handbook of Batteries and Fuel Cells, ed. David Linden, ch. 1, p. 10, McGraw-Hill (1984)) are shown below in Table I:

Table IA. Primary Batteries

	<u>Battery System</u>	<u>Anode</u>	<u>Cathode</u>
15	Leclanche	Zn	MnO ₂
	Magnesium	Mg	MnO ₂
	Alkaline MnO ₂	Zn	MnO ₂
	Mercury	Zn	HgO
	Mercad	Cd	HgO
20	Silver Oxide	Zn	Ag ₂ O
	Li/MnO ₂ Li	MnO ₂	

B. Reserve Batteries

	<u>Battery System</u>	<u>Anode</u>	<u>Cathode</u>
	Cuprous chloride	Mg	CuCl
25	Zinc/silver oxide	Zn	AgO

C. Secondary Batteries

	<u>Battery System</u>	<u>Anode</u>	<u>Cathode</u>
	Lead-acid	Pb	PbO ₂

- 10 -

	Edison	Fe	NiOOH
	Nickel-cadmium	Cd	NiOOH
	Silver-zinc	Zn	AgO
	Nickel-zinc	Zn	NiOOH
5	Silver-cadmium	Cd	AgO
	High temperature	Li(Al)	FeS
	High temperature	Na	S

The carbon microfibers increase the electrical conductivity of the cathode by forming an effective electrically conductive network throughout the chemically reducible material and physically bind or absorb liquid electrolyte dispersed throughout the cathode; the latter feature is particularly useful in Leclanche cells. Preferred microfibers are carbon fibrils having small diameters (preferably between about 3.5 and 75 nanometers), length to diameter ratios of at least 5, and graphitic layers that are substantially parallel to the fibril axis that are also substantially free of a continuous thermal carbon overcoat, as described in Tennent, U.S. Pat. No. 4,663,230; Tennent et al., U.S.S.N. 871,676; Tennent et al., U.S.S.N. 871,675; Snyder et al., U.S.S.N. 149,573; and Mandeville et al., U.S.S.N. 285,817. The fibrils may also be treated to introduce oxygen-containing functional groups onto the fibril surface, as described in McCarthy et al., U.S.S.N. 351,967.

When produced in useful quantities, the fibrils are in the form of aggregates of individual fibrils. For example, the process described in Snyder et al., U.S.S.N. 149,573 yields aggregates of randomly entangled fibrils resembling bird nests. A second type of aggregate consists

- 11 -

of clusters of individual fibrils in which the fibrils are oriented substantially parallel to each other, giving the aggregate the appearance of combed yarn. The lengths and diameters of fibrils in each cluster are essentially
5 uniform, although they may vary from cluster to cluster. These aggregates, and a method for making them, are described below and in Moy, U.S.S.N. _____ entitled "Fibril Aggregates and Method for Making Same" filed concurrently with the present application and assigned to
10 the same assignee as the present application which is hereby incorporated by reference in its entirety.

The substantially parallel graphitic layers of the individual fibrils are desirable because they enhance electrical conductivity. The small diameters enhance
15 electrolyte absorption. The lack of a continuous thermal carbon overcoat leads to enhanced electrical conductivity and oxidation resistance. The particular balance of properties chosen depends on the application for which the battery is intended. For example, in the case of alkaline
20 batteries, it is desirable to minimize the tendency of the cathode mixture to "spring back" when incorporated into the battery, thereby maximizing the amount of chemically reducible material that can be incorporated into the battery. Spring back is decreased by milling the fibrils to
25 decrease the size of the fibril aggregates and the lengths of individual fibrils, e.g., by mechanical milling using a ball or stirred ball mill or by chemical milling using

chemical reagents such as those described in McCarthy et al., U.S.S.N. 351,967. Although milling reduces
30 electrolyte absorption, the reduction is compensated by the decrease in spring back. The milling time is selected to

- 12 -

achieve an optimal balance between electrolyte absorption and spring back. On the other hand, for batteries such as Leclanche cells, high electrolyte absorption is more critical than spring back. Thus, for these batteries
5 fibrils with higher length to diameter ratios than in the case of alkaline batteries are desirable.

The Figure depicts a Leclanche battery 10 having a zinc anode 12 and a cathode 14 that is a compressed mixture of a minor portion of carbon fibrils and a major portion of
10 manganese dioxide. An aqueous electrolyte is dispersed throughout cathode 14. Zinc anode 12 is shaped to form an enclosure (e.g., a can) for housing cathode 14.

Battery 10 also features a separator 16 interposed between anode 12 and cathode 14 to prevent electrical
15 contact between the two from being established. A sealing washer 18 placed at the bottom of battery 10 also helps keep anode 12 and cathode 14 from contacting each other. A compression washer 22 and a vent washer 20 placed on top of cathode 14 help seal the contents of battery 10. An air
20 space 21 between the two washers is left. A carbon rod 24 inserted through the two washers so that it contacts cathode 14 forms a current collector for collecting current from cathode 14 when battery 10 is in use.

A jacket 26 surrounds the battery components and
25 provides environmental protection. A metal bottom 28 and a metal top 30 provide electrical connections to an external circuit (not shown).

A Leclanche battery having a zinc anode, zinc
chloride electrolyte, and a cathode made of manganese
30 dioxide admixed with carbon fibrils (prepared according to

- 13 -

the methods in the above-described patent and patent applications) was prepared as follows.

To prepare the cathode mixture, the fibrils, manganese dioxide, and mercuric chloride corrosion inhibitor were added to the bowl of a Kitchen Aid Doughmixer (model KSM90 with flat beater) and dry-mixed for 2 minutes at the slowest speed. The zinc chloride electrolyte was then added to the mixture from a sprinkler bottle over a period of 30-45 seconds with stirring.

Following the electrolyte addition, the Doughmixer speed was increased to the number 3 setting. Mixing continued at this speed for 2 1/2 minutes, after which the mixture was transferred to a glass bowl and then stored overnight inside a sealed plastic bag.

To assemble the battery, a paper liner was inserted into a zinc can (the anode). A sealing washer was then placed in the bottom of the lined can. After taring the lined can, the desired amount of the cathode mixture was added; during addition, the mixture was manually compressed using, as a compression tool, a 1 inch diameter by 3 1/2 inch long solid cylinder. The proper amount of cathode mixture was the amount necessary to fill the can to within a half inch of the top with 100-200 psi pressure.

Following addition of the cathode mixture, a compression washer was placed on the face of a compression tool sized to fit into the can for a depth of 0.5 inch; the face of the tool was machined to form a dimple for holding and centering the compression washer. The tool was then inserted into the zinc can and the compression washer driven into the can under an applied pressure of 100-200 psi.

- 14 -

Next, the compression tool was replaced with a centering tool seated in a 2 ton hydraulic press with a handle modified to accept a torque wrench for inserting a carbon rod into the battery. The centering tool was a one
5 inch long cylinder having an outside diameter designed to fit into the zinc can and an inside diameter designed to hold the carbon rod and keep it centered while it is forced down into the cathode mixture. The carbon rod was placed in the center of the tool and driven down into the battery to
10 the top of the tool. The tool was then removed and the carbon rod driven down to where it touched bottom in the hydraulic press.

Following insertion of the carbon rod, a paper seal (vent washer) was mounted on the centering tool and driven
15 down into the battery to about 1/8 inch from the top of the can. This left an empty expansion volume in the battery between the compression washer and the paper seal. A small metal cap was then placed over the exposed end of the carbon rod using the hydraulic press to seat it. Finally, hot
20 sealing wax was poured around the carbon rod on top of the paper seal to form a water-tight seal between the rod and the walls of the zinc can.

Table II contains three battery compositions prepared as described above. Each features a zinc anode, an
25 aqueous zinc chloride electrolyte, and a manganese dioxide-carbon fibril cathode. The grams of cathode mix per
~~battery refers to the amount of each cathode mix (fibrils,~~
manganese dioxide, and corrosion inhibitor moistened with electrolyte) that will fill 27 cm³ (the volume of a D-cell
30 can filled to within a half inch of the top) when compressed with a force of 150 psi. The lifetime to 0.65 volts and the

- 15 -

utilization capacity (i.e. the area under the current-time curve where time beyond 0.65 volts is not counted) was measured by connecting the battery to a 6 station D-cell battery holder with a 2.2 ohm 3 watt wirewound resistor load across each station. The percent utilization of manganese dioxide was determined by comparing the actual utilized capacity (in ampere-hours) with the theoretical utilization capacity. The latter was determined based upon the number of moles of manganese in the cathode mix. For each mole of manganese that is reduced from Mn^{+4} to Mn^{+3} , 96,500 coulombs (corresponding to 26.7 ampere-hours) are theoretically utilized.

Table II

Sample No.	1	2	3
15 Grams of cathode mix per battery	56	56	58
Grams of fibrils per battery	2.88	2.33	2.33
20 Grams of MnO_2 per battery	29.41	29.72	29.72
Grams of $ZnCl_2$ per battery	5.91	5.97	6.47
25 Grams of H_2O per battery	17.73	17.92	19.42
Lifetime to 0.65v (min.)	523	579	605
Utilized capacity (amp-hours)	4.03	4.26	4.61

- 16 -

% utilization of MnO ₂	44.7	46.7	50.6
--------------------------------------	------	------	------

The cathode can also be prepared by co-milling the chemically reducible material with the microfibers.

- 5 Moreover, it can be prepared by growing the chemically reducible material in situ within the conductive network formed by the carbon microfibers.

Fuel Cells and Metal-Air Cells

- Carbon microfibers having diameters less than or
10 equal to 0.1 μm are suitable for incorporation in the catalytic electrodes of a wide variety of fuel cells and metal-air cells. Examples of such cells are described in Handbook of Batteries and Fuel Cells, ed. David Linden, ch. 1, p. 10. They include zinc/oxygen (air) cells and
15 hydrogen/oxygen cells. The particular material for the catalytic electrode is chosen based upon the reactants, as one of ordinary skill in the art will readily appreciate. In the case of the zinc/oxygen and hydrogen/oxygen cells, the preferred catalytic material is platinum. The cells are
20 prepared using conventional fabrication techniques.

- The carbon microfibers exhibit high electronic conductivity, good corrosion resistance in alkaline and acidic environments, and high accessible surface area. In the fuel cell, they act as a support for the catalytic
25 material (holding it in place and making it accessible to the gaseous reactant) and as a current collector. In the latter application, they increase the electrical

conductivity of the electrode by forming an effective electrically conductive network throughout the catalytic
30 electrode material. Preferred microfibers are carbon fibrils having small diameters (preferably between about 3.5

- 17 -

and 75 nanometers), length to diameter ratios of at least 5, and graphitic layers that are substantially parallel to the fibril axis that are also substantially free of a continuous thermal carbon overcoat, as described in Tennent, U.S. Pat. No. 4,663,230; Tennent et al., U.S.S.N. 871,676; Tennent et al., U.S.S.N. 871,675; Snyder et al., U.S.S.N. 149,573; and Mandeville et al., U.S.S.N. 285,817. The fibrils may also be treated to introduce oxygen-containing functional groups onto the fibril surface, as described in McCarthy et al., U.S.S.N. 351,967, or milled, e.g., by mechanical milling (using a ball or stirred ball mill) or by chemical milling (using chemical reagents such as those described in the aforementioned McCarthy application) to decrease the size of fibril aggregates and the lengths of individual fibers.

When produced in useful quantities, the fibrils are in the form of aggregates of individual fibrils. For example, the process described in Snyder et al., U.S.S.N. 149,573 yields aggregates of randomly entangled fibrils resembling bird nests. A second type of aggregate consists of clusters of individual fibrils in which the fibrils are oriented substantially parallel to each other, giving the aggregate the appearance of combed yarn. The lengths and diameters of fibrils in each cluster are essentially uniform, although they may vary from cluster to cluster.

These aggregates, and a method for making them, are described below and in Moy, U.S.S.N. _____ entitled "Fibril Aggregates and Method for Making Same" filed concurrently with the present application and assigned to the same assignee as the present application which is hereby incorporated by reference in its entirety.

- 18 -

The substantially parallel graphitic layers of the individual fibrils and small diameters are desirable because they enhance electrical conductivity. The lack of a continuous thermal carbon overcoat leads to enhanced electrical conductivity and oxidation resistance.

Fibril Aggregates and Method of Preparing Same

We now describe the structure and preparation of preferred fibril aggregates.

Structure

Preferred fibril aggregates consist of bundles of straight to slightly bent or kinked carbon fibrils in which the individual fibrils have substantially the same relative orientation, e.g., the longitudinal axis of each fibril (despite individual bends or kinks) extends in the same direction as that of the surrounding fibrils in the bundle. This arrangement of individual fibrils gives the aggregates the appearance of combed yarn, in contrast to aggregates such as those produced according to the process described in the aforementioned Snyder et al. application, U.S.S.N. 149,573, in which the fibrils are randomly entangled with each other to form tightly entangled balls of fibrils resembling bird nests.

The carbon fibrils within each fibril aggregate preferably have diameters between about 3.5 and 75 nanometers, length to diameter ratios of at least 5, and graphitic layers that are substantially parallel to the longitudinal fibril axis, and are also substantially free of a continuous thermal carbon overcoat, as described in Tennent, U.S. Pat. No. 4,663,230; Tennent et al., U.S.S.N. 871,676; Tennent et al., U.S.S.N. 871,675; Snyder et al., U.S.S.N. 149,573; and Mandeville et al., U.S.S.N. 285,817.

- 19 -

The aggregates may also be treated to introduce oxygen-containing functional groups onto the surface of individual fibrils, as described in McCarthy et al., U.S.S.N. 351,967. Within each fibril aggregate, the
5 diameters and length to diameter ratios of the individual fibrils are essentially uniform.

A second type of fibril aggregate consists of straight to slightly bent or kinked fibrils which are loosely entangled with each other to form an "open mat"
10 structure. The degree of entanglement is greater than observed in the combed yarn aggregates (in which the individual fibrils have substantially the same relative orientation) but less than that of the tightly entangled fibril balls formed according to the process described in
15 Snyder et al., U.S.S.N. 149,573.

Preparation

In general, both the combed yarn and open mat aggregates are prepared by contacting an iron or iron-containing metal catalyst particle deposited on a
20 support material having one or more readily cleavable surfaces and a surface area of at least $1 \text{ m}^2/\text{g}$ with a carbon-containing gas in a reactor at $400\text{--}850^\circ\text{C}$ using the procedures described in the aforementioned Tennent patent and Tennent, Snyder, and Mandeville applications.

25 Preferred support materials include γ -alumina or magnesia in the form of aggregates of tabular, prismatic, or platelet crystals. ~~Such material is commercially available,~~
e.g., from Strem Chemicals (in the case of γ -alumina) and Alfa Inorganics (in the case of magnesia). The γ -alumina
30 supports yield primarily combed yarn aggregates, while the magnesia supports yield primarily open mat aggregates. In

- 20 -

contrast, the use of supports consisting of spherical particles or aggregates lacking cleavable planar surfaces (e.g., supports made of Degussa fumed alumina as described in the aforementioned Snyder et al. application) leads
5 primarily to tightly entangled fibril balls.

While not wishing to be limited to any particular theory, it is believed that the readily cleavable planar surfaces of the support allow the fibrils to assist each other as they grow, creating a "neighbor effect" that, in
10 the case of the γ -alumina support, leads to a combed yarn fibril aggregate in which the individual fibrils have the same relative orientation. Spherical supports, on the other hand, lack this effect, leading to tightly entangled balls of randomly oriented fibrils. The magnesia support,
15 although having readily cleavable planar surfaces, yields primarily lightly entangled, open mat fibril aggregates because it breaks apart more readily than the γ -alumina support during fibril growth, resulting in aggregates that are less ordered than the combed yarn aggregates but more
20 ordered than the tightly entangled fibril balls. The oxide precursors used to generate the metal catalyst particles also affect the tendency of the support to break apart. The more readily the oxide and support can form a mixed oxide at the interface between them, the more likely the support is
25 to break apart.

The following examples describe the preparation of combed yarn and open mat fibril aggregates.

Example 1

This example describes the preparation of combed
30 yarn fibril aggregates.

- 21 -

200 gm of γ -alumina (Strem Chemicals) was heated at 230°C in a vacuum oven under reduced pressure (25 in. mercury vacuum) for 5 hrs. Next, it was slurried at room temperature with a solution containing 200 gm $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ in 800 cm³ methanol and the slurry agitated thoroughly for 1 hr. The methanol was then removed in a rotary evaporator by gradually reducing pressure and increasing temperature to boil off the methanol at a reasonable rate; final conditions were 25 in. mercury vacuum and temperature less than or equal to 55°C. The stripping process took approximately 45 minutes.

After the methanol had been removed, the remaining solids were dried at 160°C under reduced pressure (15-20 in. mercury vacuum) in a vacuum oven overnight; the typical catalyst yield after drying was 270 gm. Iron loadings were calculated from starting amounts of $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ and final weights of dried catalysts. Typical iron loadings ranged from 8-11%.

Fibrils were grown at 680°C in a 1 in. quartz tube inserted into an electrical furnace. The catalyst was introduced into the reactor at 680°C as a free-flowing powder in a preheated gas stream consisting of 2 parts ethylene and 1 part hydrogen at a flow rate of about 2 liters/min., and deposited on a quartz wool plug placed in contact with a thermocouple in the center of the tube.

In a typical run, 0.100 gm catalyst yielded approximately 1.0 gm carbon fibrils after 4 hrs. at run conditions. The yield of carbon fibrils is expressed as a factor times the weight of catalyst or the weight of iron. Typical yields for this catalyst were 10-11 times based on catalyst and 100-125 times based on iron. Examination of

- 22 -

the fibrils using electron microscopy (SEM and STEM) revealed the fibrils to be present as aggregates of straight to gently curving fibrils having the appearance of skeins of brushed or combed yarn. The aggregates generally were still
5 attached to the alumina support.

Example 2

15.10 gm of γ -alumina (Strem Chemicals) was slurried in a solution of 14.9 gm $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ in 400 cm^3 methanol for 1 hour at room temperature. Methanol was then
10 removed under reduced pressure in a rotary evaporator and dried in a vacuum oven as in Example 1. The calculated cobalt loading was 17.2% by weight.

Fibrils were grown at 680°C according to the procedure described in Example 1. Examination of the
15 fibrils by TEM revealed numerous combed yarn fibril structures in which the individual fibrils were kinked or twisted. The longitudinal axes of the fibrils, however, had the same relative orientation. The fibrils were hollow and had diameters less than 10 nanometers.

Example 3

14.3 gm γ -alumina (Strem Chemicals) was slurried in a solution of 8.3 gm $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ in 400 cm^3 methanol for 1 hour at room temperature. Methanol was then removed under
25 reduced pressure in a rotary evaporator and dried in a vacuum oven as in Example 1. The calculated nickel loading was 16.3% by weight.

~~Fibrils were grown according to the procedure in~~

Example 1. TEM analysis revealed small combed yarn-type aggregates in which the individual fibrils were straight and
30 had diameters of about 15 nanometers.

- 23 -

Example 4

16.51 gm γ -alumina (Strem Chemicals) was slurried with a solution of 30.2 gm $\text{Mn}(\text{NO}_3)_2$ (50% solution in H_2O) dissolved in 400 cm^3 methanol. Methanol was then removed under reduced pressure in a rotary evaporator and dried in a vacuum oven as in Example 1. The calculated manganese loading was 16.3% by weight.

Fibrils were grown according to the procedure in Example 1. TEM analysis revealed combed yarn-type aggregates in which the individual fibrils were slightly tangled.

Example 5

15.11 gm γ -alumina (Strem Chemicals) was slurried with a solution containing 13.8 gm $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ and 11.1 gm $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ dissolved in 400 cm^3 methanol for 1 hour at room temperature. Methanol was then removed under reduced pressure in a rotary evaporator and dried in a vacuum oven as in Example 1. The calculated zinc and copper loadings were 19.1% and 12.9% by weight, respectively.

Fibrils were grown according to the procedure in Example 1. TEM analysis revealed a mixture of combed yarn-type aggregates in which the individual fibrils were straight and had diameters less than 10 nanometers and hollow, open, straight fibrils with diameters less than 10 nanometers.

Example 6

~~This example describes the preparation of open mat~~
fibril aggregates.

74 gm magnesia platelets (Alfa Inorganics) was slurried with 400 gm deionized water at 65-70°C for 1 hr. with rapid stirring in a baffled reactor. A solution of 112

- 24 -

gm $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ and 5.4 gm $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ in 150 cm³ deionized water was added dropwise over a period of about 1 hr. at 65°C while maintaining rapid stirring. During the addition, the solids turned chocolate brown.

- 5 After addition was complete, the slurry was filtered; the supernatant was colorless (pH = about 5) and the solids were a dark red-brown. After washing several times with deionized water, the solids were dried overnight at 160°C under reduced pressure (15-20 in. mercury vacuum).
- 10 A typical yield of dried solids was 105 gm. The solids were then calcined at 400°C for 4 hrs. to yield 74 gm catalyst. Iron and molybdenum loadings were calculated to be 20.8% and 4.0%, respectively.

- Fibrils were grown using the procedure described in
- 15 Example 1. Typical fibril yields were 20-25 times based on catalyst, 120-150 times based on iron. Examination by electron microscopy (SEM and STEM) showed that the fibrils were present primarily as loose, open mats with lesser amounts of combed yarn aggregates.

- 20 Other suitable support materials include MoO_3 and layered clays, e.g., alumina-, silica-, or magnesia-based clays.

Other embodiments are within the following claims.

- 25 -

Claims

1. A fibril aggregate comprising a multiplicity of carbon fibrils whose longitudinal axes have substantially the same relative orientation, each of said fibrils
5 characterized as having graphitic layers that are substantially parallel to its longitudinal axis and being free of a continuous thermal carbon overcoat.
2. The fibril aggregate of claim 1 wherein the diameters of at least 90% of the individual fibrils in said
10 aggregate have diameters that are between 3.5 and 75 nanometers.
3. The fibril aggregate of claim 1 wherein the diameters of substantially all of the individual fibrils in said aggregate are between 3.5 and 75 nanometers,
15 inclusive.
4. The fibril aggregate of claim 1 wherein the diameter of said aggregate is between 0.05 and 50 μm , inclusive, and the length of said aggregate is between 0.1 and 1000 μm , inclusive.
- 20 5. The fibril aggregate of claim 1 wherein at least 90% of the individual fibrils in said aggregate have a length to diameter ratio of at least 5.
-
6. The fibril aggregate of claim 1 wherein substantially all of the individual fibrils in said
25 aggregate have a length to diameter ratio of at least 5.

- 26 -

7. A process for preparing an aggregate of carbon fibrils comprising contacting a particulate metal catalyst deposited on a support having one or more readily cleavable planar surfaces and a surface area of at least $1 \text{ m}^2/\text{gm}$ with
5 a carbon-containing gas in a reactor at reaction conditions including temperature sufficient to produce said aggregate.
8. The process of claim 7 wherein said support is a metal oxide.
9. The process of claim 7 wherein said support is
10 γ -alumina in the form of aggregates of tabular, prismatic, or platelet crystals.
10. The process of claim 7 wherein said support is magnesia in the form of tabular, prismatic, or platelet crystals.
11. The process of claim 7 wherein said catalyst
15 comprises iron.
12. The process of claim 11 wherein said catalyst comprises iron and at least one element chosen from Groups V, VI, or VII, or the lanthanides.
13. The process of claim 12 wherein said element is
20 molybdenum.
-
14. The process of claim 12 wherein said element is chromium.

- 27 -

15. The process of claim 12 wherein said element is manganese.

16. The process of claim 12 wherein said element is tungsten.

5 17. The process of claim 12 wherein said element is vanadium.

18. The process of claim 12 wherein said element is cerium.

10 19. The process of claim 7 wherein said catalyst comprises cobalt.

20. The process of claim 7 wherein said catalyst comprises nickel.

21. The process of claim 7 wherein said catalyst comprises manganese.

15 22. The process of claim 7 wherein said catalyst comprises zinc and copper.

23. The process of claim 7 wherein said temperature is between 400 and 850°C.

20 24. The process of claim 7 wherein said temperature is between 600 and 750°C.

- 28 -

25. The process of claim 7 wherein said aggregate comprises a multiplicity of fibrils whose longitudinal axes have substantially the same relative orientation, each of said fibrils characterized as having graphitic layers that are substantially parallel to its longitudinal axis and being free of a continuous thermal carbon overcoat.

26. The process of claim 7 wherein said particulate metal catalyst comprises iron; said support is γ -alumina in the form of aggregates of tabular, prismatic, or platelet crystals; and said aggregate comprises a multiplicity of fibrils whose longitudinal axes have substantially the same relative orientation, each of said fibrils characterized as having graphitic layers that are substantially parallel to its longitudinal axis and being free of a continuous thermal carbon overcoat.

27. An aggregate of carbon fibrils prepared according the process of claim 7.

28. A particulate, carbon fibril-forming, metal catalyst deposited on a support having one or more readily cleavable planar surfaces and a surface area of at least 1 m²/gm.

29. The catalyst of claim 28 wherein said support is a metal oxide.

30. The catalyst of claim 28 wherein said support is γ -alumina in the form of aggregates of tabular, prismatic, or platelet crystals.

- 29 -

31. The catalyst of claim 28 wherein said support is magnesia in the form of aggregates of tabular, prismatic, or platelet crystals.

32. The catalyst of claim 28 wherein said catalyst
5 comprises iron.

33. The catalyst of claim 32 wherein said catalyst comprises iron and at least one element chosen from Groups V, VI, or VII, or the lanthanides.

34. The catalyst of claim 33 wherein said element
10 is molybdenum.

35. The catalyst of claim 33 wherein said element is chromium.

36. The catalyst of claim 33 wherein said element is manganese.

37. The catalyst of claim 33 wherein said element
15 is tungsten.

38. The catalyst of claim 33 wherein said element is vanadium.

39. The catalyst of claim 33 wherein said element
20 is cerium.

40. The catalyst of claim 28 wherein said catalyst comprises cobalt.

- 30 -

41. The process of claim 28 wherein said catalyst comprises nickel.

42. The process of claim 28 wherein said catalyst comprises manganese.

5 43. The process of claim 28 wherein said catalyst comprises zinc and copper.

10 44. In a battery comprising an anode, a cathode that includes a chemically reducible material into which is incorporated an amount of an electrically conductive material sufficient to enhance the electrical conductivity of said chemically reducible material, and an electrolyte, the improvement wherein said electrically conductive material comprises carbon microfibers.

15 45. The battery of claim 44 wherein the diameter of said microfibers is no greater than 0.1 micron.

46. The battery of claim 44 wherein the length to diameter ratio of said microfibers is at least 5.

20 47. The battery of claim 44 wherein said microfibers comprise tubes having graphitic layers that are substantially parallel to the microfiber axis and diameters between 3.5 and 75 nanometers, inclusive.

48. The battery of claim 47 wherein said microfibers are substantially free of a continuous thermal carbon overcoat.

- 31 -

49. The battery of claim 47 wherein said microfibers are in the form of aggregates in which individual microfibers are randomly entangled with each other.

5 50. The battery of claim 47 wherein said microfibers are in the form of aggregates in which individual microfibers are oriented substantially parallel to each other.

10 51. The battery of claim 44 wherein said battery is a primary battery.

52. The battery of claim 51 wherein said primary battery is a Leclanche battery.

15 53. The battery of claim 52 wherein the amount of microfibers incorporated into said cathode is less than or equal to 0.5 grams per gram of said chemically reducible material.

20 54. The battery of claim 53 wherein the amount of microfibers incorporated into said cathode is less than or equal to 0.2 grams per gram of said chemically reducible material.

~~55. The battery of claim 44 wherein said battery is~~
a secondary battery.

56. The battery of claim 44 wherein said battery is a reserve battery.

- 32 -

57. The battery of claim 44 wherein said battery is an alkaline battery.

58. The battery of claim 57 wherein said alkaline battery is an alkaline zinc - manganese dioxide battery.

5 59. The battery of claim 58 wherein the amount of microfibers incorporated into said cathode is less than 0.5 grams per gram of said chemically reducible material.

60. The battery of claim 59 wherein the amount of microfibers incorporated into said cathode is less than 0.2
10 grams per gram of said chemically reducible material.

61. The battery of claim 44 wherein said chemically reducible material comprises a metal oxide.

62. The battery of claim 61 wherein said metal oxide is selected from the group consisting essentially of
15 MnO_2 , HgO , Ag_2O , AgO , PbO_2 , and NiOOH .

63. The battery of claim 44 wherein said chemically reducible material comprises a metal chloride.

64. The battery of claim 63 wherein said metal chloride is CuCl .

20 65. The battery of claim 44 wherein said chemically reducible material comprises sulfur or a metal sulfide.

- 33 -

66. The battery of claim 65 wherein said metal sulfide is FeS.

67. The battery of claim 44 wherein said anode is selected from the group consisting essentially of zinc,
5 lithium, cadmium, silver, magnesium, iron, sodium, lithium-aluminum alloy, and lead metal.

68. In a Leclanche battery comprising a zinc anode, a manganese dioxide cathode into which is incorporated an amount of an electrically conductive
10 material sufficient to enhance the electrical conductivity of said manganese dioxide, and an electrolyte,
the improvement wherein said electrically conductive material includes carbon microfibers which comprise tubes having graphitic layers that are
15 substantially parallel to the microfiber axis and diameters between 3.5 and 75 nanometers, inclusive.

69. In an alkaline zinc - manganese dioxide battery comprising a zinc anode, a manganese dioxide cathode into which is incorporated an amount of an electrically
20 conductive material sufficient to enhance the electrical conductivity of said manganese dioxide, and an alkaline electrolyte,

the improvement wherein said electrically
~~conductive material includes carbon microfibers which~~
25 comprise tubes having graphitic layers that are substantially parallel to the microfiber axis and diameters between 3.5 and 75 nanometers, inclusive.

- 34 -

70. A method of preparing a cathode for a battery comprising combining a chemically reducible material with an amount of carbon microfibers sufficient to enhance the electrical conductivity of said chemically reducible
5 material.

71. The method of claim 70 further comprising milling said microfibers.

72. The method of claim 71 wherein said microfibers are mechanically milled.

10 73. The method of claim 71 wherein said microfibers are chemically milled.

74. The method of claim 71 wherein said microfibers are co-milled with said chemically reducible material.

75. The method of claim 70 wherein said
15 combination is effected by growing said chemically reducible material in situ within the electrically conductive network formed by said carbon microfibers.

76. In an electrochemical cell comprising a catalytic electrode on which an electrochemical reaction
20 occurs,

~~the improvement wherein carbon microfibers having~~
diameters less than or equal to 0.1 micron are incorporated in said electrode in an amount sufficient to enhance the electrical conductivity of said electrode.

- 35 -

77. The electrochemical cell of claim 76 wherein the length to diameter ratio of said microfibers is at least 5.

78. The electrochemical cell of claim 76 wherein
5 said microfibers comprise tubes having graphitic layers that are substantially parallel to the microfiber axis and diameters between 3.5 and 75 nanometers, inclusive.

79. The electrochemical cell of claim 78 wherein
10 said microfibers are substantially free of a continuous thermal carbon overcoat.

80. The electrochemical cell of claim 78 wherein said microfibers are in the form of aggregates in which individual microfibers are randomly entangled with each other.

15 81. The electrochemical cell of claim 78 wherein said microfibers are in the form of aggregates in which individual microfibers are oriented substantially parallel to each other.

82. The electrochemical cell of claim 76 wherein
20 said cell is a fuel cell.

83. The electrochemical cell of claim 82 wherein
said fuel cell is a hydrogen/oxygen fuel cell.

84. The electrochemical cell of claim 76 wherein said cell is a metal-air cell.

- 36 -

85. The electrochemical cell of claim 84 wherein said metal is zinc.

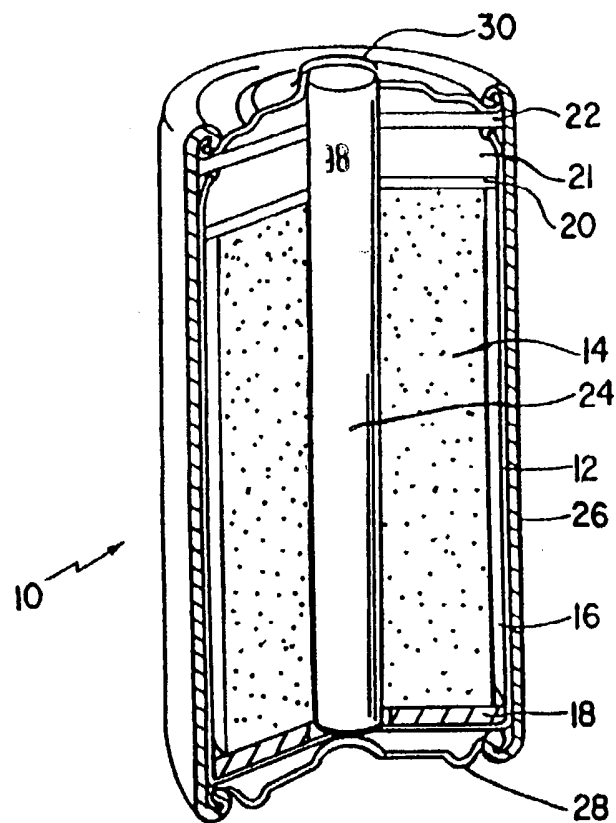
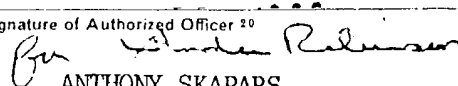


FIG. 1

INTERNATIONAL SEARCH REPORT

International Application No

PCT/US90/05498

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) ³		
According to International Patent Classification (IPC) or to both National Classification and IPC IPC(5): D01F 9/12 B32B 9/00 C01B 31/04 US CL.: 423/447.3, 447.1 428/367, 376, 398, 408 427/216, 249 264/29.2		
II. FIELDS SEARCHED		
Minimum Documentation Searched ⁴		
Classification System	Classification Symbols	
US CL.	423/447.3, 447.1 502/182, 185, 438 428/367, 368, 376, 398, 408 427/216, 249, 255.1 264/29.2	
Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched ⁶		
III. DOCUMENTS CONSIDERED TO BE RELEVANT ¹⁴		
Category *	Citation of Document, ¹⁶ with indication, where appropriate, of the relevant passages ¹⁷	Relevant to Claim No. ¹⁸
X	US, A, 4,663,230 (TENNET) 05 May 1987 See the entire document.	1-27
Y	US, A, 4,518,575 (PORTER et al.) 21 May 1985 See the entire document.	1-27
Y	JP, A, 57-117622 (DENKO) 22 August 1982 See the entire document.	1-27
Y	JP, A, 59-152299 (ENDO) 30 August 1984 See the entire document.	1-27
Y	Journal of Catalysis, Vol. 30, 1976 R.T.K. Baker et al., "Formation of Filamentous Carbon from Iron, Cobalt and Chromium Catalyzed Decomposition of Acetylene" pages 86-95.	1-27
Y	Journal of Crystal Growth, Vol. 32, 1976 A. Oberlin et al., "Filamentous Growth of Carbon Through Benzene Decomposition" pages 335-349.	1-27
<div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p>* Special categories of cited documents: ¹⁵</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> </div> <div style="width: 45%;"> <p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>"Δ" document member of the same patent family</p> </div> </div>		
IV. CERTIFICATION		
Date of the Actual Completion of the International Search ²	Date of Mailing of this International Search Report ²	
12 DECEMBER 1990	23 JAN 1991	
International Searching Authority ¹	Signature of Authorized Officer ²⁰	
ISA/US	 ANTHONY SKAPARS	

FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

V. ☐ OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE¹

This international search report has not been established in respect of certain claims under Article 17(2) (a) for the following reasons:

1. ☐ Claim numbers _____, because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claim numbers _____, because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out¹, specifically:

3. ☐ Claim numbers _____, because they are dependent claims not drafted in accordance with the second and third sentences of PCT Rule 6.4(a).

VI. ☒ OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING²

This International Searching Authority found multiple inventions in this international application as follows:

See extra sheet.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.
2. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:
3. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers: **1-27**
Telephone practice (10 December 1990, Ms. Dorothy Whelan)
4. ☐ As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

- ☐ The additional search fees were accompanied by applicant's protest.
- ☐ No protest accompanied the payment of additional search fees.

- I. Claims 1-27 are drawn to fibril aggregate and process for preparing aggregate of fibrils.
- II. Claims 28-43 are drawn to catalyst.
- III. Claims 44-69 and 76-85 are drawn to a battery.
- IV. Claims 70-75 are drawn to a method of preparing a cathode.

There is no unity of invention between Group I and Group II because the process of Group I does not produce the product (catalyst) of Group II. Group III and Group II are drawn to different products. Group IV does not produce the product (battery) of Group III.
